Coordinated Beamforming, Interference-Aware Power Control, and Scheduling Framework for 6G Wireless Networks

Yongjae Kim, Bang Chul Jung, and Youngnam Han

Abstract—**In this study, we propose a novel sum-rate enhancement framework for future 6G multi-cell multiple-input multiple-output (MIMO) uplink networks, which exploits the coordinated beamforming, power control, and user scheduling (CBPS) technique. The proposed CBPS technique not only significantly mitigates the inter-cell interference in transmit beamforming for users but also eliminates the intra-cell interference among the users in the same cell the receive beamforming at base stations (BSs). Additionally, we propose a user scheduling algorithm that selects the users whose effective channel vectors are mutually orthogonal to each other to increase the spectral efficiency and an interference-aware power control technique for users to further reduce inter-cell interference. It is worth noting that the proposed CBPS framework does not require information exchange among the BSs and operates in a non-iterative and distributed manner based on local channel state information (CSI) at both the BSs and users. Thus, it can be implemented for practical wireless systems with low complexity. Extensive simulation results show that the proposed CBPS framework significantly outperforms conventional techniques in multi-cell environments.**

Index Terms—**Coordinated beamforming, interference management, MIMO, power control, 6G, user scheduling algorithm.**

I. INTRODUCTION

FUTURE 6G wireless communication systems are expected to support a massive number of devices such as smart phones, tablet computers, smart home sensors, etc [1], [2]. As the number of connected devices grows, interference is considered to be one of the most critical factors that limits the performance of wireless networks. In 5G new radio (NR), for example, both the user-side and network-side interference management schemes have been studied with advanced receivers and coordination techniques among multiple base statios (BS), respectively [3], [4]. The interference can be considered in two ways: Interference exploitation and interference mitigation [5], [6]. The former indicates that signals from inter-cells are used in decoding messages where BSs share information such as channel state information (CSI) and data signals of their associated users and it is referred to as networked multiple-input multiple-output (MIMO). In [7], a multi-cell cooperative downlink channel was studied for the first time. The authors applied *dirty paper coding (DPC)* to an ideal backhaul network for each user and BS with a single antenna. For MIMO, [8] studied the BS cooperation to mitigate cochannel interference by joint transmission schemes. However, for the interference exploitation method, practical issues such as limited-capacity backhaul links and synchronization between BSs should be addressed. The latter, interference mitigation, is a way to reduce the effect of signals from neighboring cells by power allocation, beamforming, and user scheduling without the BS cooperation and user data sharing. In [9], a joint transmit beamforming and power control problem for the multi-cell environment was first considered and an iterative algorithm was proposed to optimize the beamforming vector and power allocations based on an uplink-downlink duality property. In [10], an efficient iterative algorithm was proposed for coordinated beamforming vectors across all BSs in decentralized multi-cell downlink based on uplink-downlink duality using the Lagrangian theory. Recently, a two-layer decoding method was evaluated to reduce interference in multi-cell MIMO networks [11]. Also, in [12], a novel transmit precoding algorithm was proposed for multiple access spatial modulation MIMO based on the primal-dual optimality theory. In [13], a deep learing-based low overhead analog beam selection scheme by virtue of the super-resolution technology was developed and a beam quality prediction model was formulated. When the maximum ratio combining (MRC) and random choice of large-scale-fading decoding (LSFD), which were introduced in [14], [15], were used in the first and second decoding layers, respectively, the closed form of the uplink spectral efficiency was derived for the correlated Rayleigh fading environment. To maximize the spectral efficiency, an iterative algorithm was proposed and a local optimum could be obtained.

An iterative algorithm, however, leads to a lot of signaling overhead; thus, the non-iterative algorithm is more suitable for conventional cellular networks. Different from above, Chae *et al.* proposed a closed-form expression for the transmit

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beamforming vectors under a single-cell multi-user MIMO downlink channel [16]. Additionally, a new limited feedback algorithm to avoid full channel quantization was considered. They also proved that the iterative algorithm for beamforming vectors converges to generalized eigenvectors of normalized matched channel matrices, which are defined as channel matrices. However, the proposed method in [16] can be used only when two active users are served simultaneously. In [17], a non-iterative algorithm for the coordinated beamforming problem was evaluated to mitigate the inter-cell interference in the multi-cell environment. Their proposed algorithms are optimal with respect to the degree of freedom (DoF) of a two-cell downlink MIMO channel, where two receive antennas are equipped at each user. In case of more than two-cell scenarios, a physical beam-switching scheme was applied to mitigate inter-cell interference.

In the multi-user system, scheduling can be considered to achieve benefits such as multiplexing gain, multi-user diversity gain, fairness among users, and so on. In [18], scheduling algorithms for the multi-user system based on MIMO were introduced and the tradeoff between multiplexing and multi-user diversity gain was evaluated. Additionally, a cross-layer design considering the physical and medium access control (MAC) layer was proposed for the effective scheduling algorithm. To consider a tradeoff between the sum-rate and fairness, the concept of proportional fairness (PF) was proposed by Kelly *et al.* [19] and PF schedulers for orthogonal frequency division multiple access (OFDMA) systems were considered in [20], [21]. In [22], the authors proposed a scheme to intentionally induce a random fading effect by opportunistic beamforming when there are enough users in a slow fading or little scattering environment and the performance gain is achieved from the multi-user diversity effect. Additionally, there are novel transmission schemes for cell-edge users affected by inter-cell interference in massive MIMO networks [23], [24]. In [23], the proposed cell-edge-aware zero-forcing (CEA-ZF) precoder exploits spatial dimensions to suppress inter-cell interference for downlink massive MIMO networks, and it was shown that CEA-ZF can improve the performance in terms of the data rate and coverage. In [24], a CEA-ZF with a block diagonalization (BD) cooperative precoding algorithm was proposed to suppress interference by exploiting the spatial degrees of freedom in two-tier heterogeneous massive MIMO networks. Therefore, a simultaneous user scheduling and beamforming technique should be considered for cellular networks where a BS and a user are equipped with multiple antennas.

A. Related Works

In multi-cell environment, there have been a few studies considering simultaneously coordinated beamforming and scheduling where inter-cell interference is considered [25]–[34]. In [25], opportunistic beamforming was considered for downlink the multiple-input single-output (MISO) system where a clustering-based adaptive feedback scheme is exploited. Additionally, a modified PF scheduler was proposed to accommodate various quality-of-service (QoS) classes and adjust fairness levels. In [26], a joint precoding and scheduling algorithm was proposed for MISO networks. In the proposed algorithm, users are grouped based on spatial channel correlation information and then a two-step precoding method is adopted to mitigate the effect of interference and obtain spatial multiplexing gain. Additionally, the users are scheduled by the proposed greedy scheduling algorithm based on the PF metric. In the context of interference exploitation, the inter-cell interference can be managed by BS cooperation [27], [28]. In [27], analytical expressions for system spectral efficiency were derived when multiple BSs employed joint transmission with linear ZF beamforming to eliminate the intra-cluster interference. Additionally, the authors developed a downlink scheduling algorithm satisfying fairness requirements. In [27], a joint optimization of beamforming and power control was studied for a coordinated multi-cell MISO networks. To maximize the minimum weighted signal-to-interference-plus-noise ratio (SINR), a distributed algorithm that only requires statistical information was proposed using the nonlinear Perron-Frobenius theory and network duality. In [28], joint transmission strategies and resource allocation schemes were studied to examine the benefit of BS coordination. The key idea is decoupling the joint optimization problem into scheduling, beamforming, and power allocation sub-problems and solving it in an iterative fashion.

In [29]–[33], several coordinated beamforming techniques and user scheduling algorithms without BS cooperations (i.e., only using local CSI) were proposed under the opportunistic interference alignment (OIA) framework, which was also introduced in [35], [36]. The basic idea of OIA is to combine the user scheduling algorithm and classical interference alignment (IA) framework to take advantage of the multi-user diversity. In [29], they proved that the optimal DoF can be achieved where the number of users in each cell scales as a function of signal-to-noise-ratio (SNR), which is referred to as the *user scaling law* introduced in [37], for single-input multiple-output (SIMO) interfering multiple access channel (IMAC) (i.e., uplink). In [30], it was shown that M DoF can be achieved by opportunistically selecting a single user whose received interference is most aligned with other users for a 3-transmitter MIMO interfering broadcast channel (IBC) (i.e., downlink) with a constrained number of antennas. The authors in [31] researched an optimal way of exploiting multi-user diversity for K-cell SIMO networks extended to MIMO IBC networks. In [31], the authors analyzed the relation between the number of users and *interference alignment measure* by geometrical interpretation and derived the sufficient number of users to achieve target DoF. In [32], antenna selected-based OIA and singular value decomposition (SVD)-based OIA were proposed for MIMO IMAC with the ZF receiver at the BSs. It was shown that the user scaling condition is analyzed for the number of users required to achieve the optimal DoF when a proper scheduling algorithm that selects users with the smallest *leakage of interference (LIF)* metrics is applied. In [33], OIA schemes with a limited feedback approach were also studied for MIMO IBC. They evaluated both Grassmannian and random codebooks-based limited feedback methods that can achieve the same user scaling condition as that of [32]. Furthermore, they proposed an improved OIA scheme with respect to the sum-rate using the semi-orthogonal user selection (SUS) algorithm [38]. In [34], joint user selection, power allocation, and a precoding scheme were proposed in multi-cell MIMO networks when imperfect CSI is assumed. To maximize the sum-spectral efficiency, the authors formulated the optimization problem as the maximization of the product of Rayleigh quotients and then an iterative algorithm that satisfies the first-order optimality condition of optimization problem was developed. The proposed precoding solution in [34], however, needs some iterations to converge.

B. Contributions

In this study, we propose an interference-aware combined coordinated beamforming, power control, and scheduling (CBPS) framework for multi-cell MIMO uplink networks where each cell consists of a BS with M antennas and N users with L antennas. The proposed framework consists of a combined procedure with transmit beamforming, user scheduling, power control and receive beamforming to mitigate interference and improve spectral efficiency. More specifically, a transmit beamforming vector at each user is designed to minimize the LIF, which is the amount of generated interference to neighboring BSs, based on their signal subspaces. Subsequently, each user feeds its LIF scalar metric and effective channel vector back to its associated BS for user scheduling and information decoding. With only local CSI from associated users, each BS selects S users with the most orthogonal effective channel vectors to those of other users for spectral efficiency in a distributed manner. Additionally, we adopt an efficient user scheduling algorithm that selects users with the most orthogonal effective channel vectors to those of previously selected users for spectral efficiency where a ZF-based receive beamforming is employed. The proposed power control technique allows that users with large LIF values to be scheduled by reducing their transmit power. It can increase the sum-rate performance with the user scheduling algorithm by user selection diversity gain. After the uplink transmissions of the scheduled users, linear ZF beamforming is used to perfectly eliminate the intra-cell interference when the number of scheduled users is less than or equal to the number of antennas at each BS, i.e., $S \leq M$. The complexity and amount of feedback of the proposed framework are studied for 5G NR systems and their applications.

The main contributions of this study are as follows.

- *Non-iterative and linear beamforming algorithm:* Because the iterative beamforming algorithms [9], [10], [39], [40] need a lot of signaling overhead, they are not suitable for practical systems. Additionally, because DPC-like non-linear algorithms require precise time and phase synchronization of the signals from BSs, linear processing solutions such as ZF or channel inversion have received considerable attention [32], [33], [38]. Our proposed framework can resolve convergence, complexity, and signaling overhead problems of iterative and non-linear algorithms using SVD operations and ZF filtering when transmit and receive beamforming vectors are constructed. Accordingly, the proposed methods can be applied to practical systems, i.e., LTE or 5G NR.
- *Applicable to the practical distributed systems:* We propose a distributed CBPS framework only with local CSI for multi-cell multi-user MIMO uplink networks. Based on the transmit beamforming vector and signal subspaces of BSs, each user feeds the LIF scalar metric and effective channel vector back to its associated BS for user scheduling and information decoding. Because each BS independently selects users for uplink data transmissions, there is no burden for cooperation and information exchange among BSs. Therefore, the CBPS framework can be applied to the practical multi-cell multi-user MIMO distributed systems.
- *Possible to enhance the sum-rate enhancement:* The proposed scheme can ameliorate the sum-rate performance compared with conventional schemes by managing the inter-cell interference as well as intra-cell interference and selecting proper users with the most orthogonal effective channel vectors to those of previously selected users.

C. Organization

The rest of this paper is organized as follows. In Section II, the system model is described. Section III presents the proposed CBPS framework. In Section IV, the computational complexity and amount of information exchange of the proposed framework are analyzed. The performance of the proposed framework is evaluated by extensive simulations in Section V. Finally, the conclusions are drawn in Section VI.

D. Notations

Throughout this paper, the upper case boldface denotes a matrix, the lower case boldface denotes a vector, $\mathbf{A}^H$ denotes the conjugate transpose of matrix $\mathbf{A}$ and $\|\mathbf{A}\|$ denotes the matrix two-norm. Additionally, the notations $\mathbb{E}[\cdot]$ denotes expectation and $\mathbb{C}^{M\times L}$ denotes the set of $M \times L$ complex matrices.

II. SYSTEM MODEL

We consider K-cell[1] MIMO uplink networks where each cell consists of a BS with M antennas and N users with L antennas each, as shown in Fig 1. The time division duplex (TDD) is considered as in 5G NR. Each BS selects S ($S \leq M$) users for uplink transmission and each selected user transmits a single data stream to its associated BS. We assume the case when $L < (K-1)S+1$; otherwise all inter-cell interference can be perfectly eliminated by transmit beamforming and it will be discussed in Section III-B.

The channel from the jth user in the ith BS to the kth BS is denoted by $\beta_k^{[i,j]}\mathbf{H}_k^{[i,j]}$, where $\beta_k^{[i,j]}$ and $\mathbf{H}_k^{[i,j]} \in \mathbb{C}^{M\times L}$ denote the large-scale path-loss gain and the small-scale fading channel matrix, respectively, from the jth user in the ith BS to the

[1] In this study, we assume that there are K BSs nearby the home BS that have a large amount of interference, and the interference signal from the other distant BSs can be considered as a Gaussian noise.

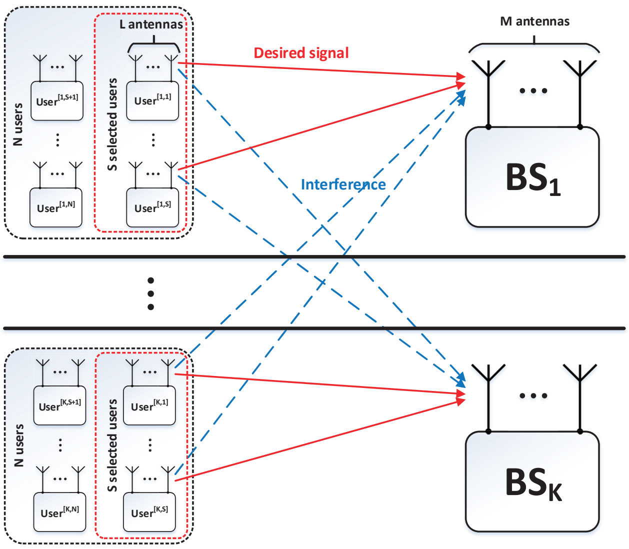


Fig. 1. K-cell uplink MIMO model

kth BS for $i, k \in \mathcal{K} = \{1, \cdots, K\}$ and $j \in \mathcal{N} = \{1, \cdots, N\}$. Here, $0 < \beta_k^{[i,j]} = \left(d_k^{[i,j]}\right)^{-\alpha} \leq 1$, where $\left(d_k^{[i,j]}\right)^{-\alpha} > 0$ denotes the distance from user j in BS i to BS k and α denotes the path-loss exponent. Additionally, each element of $\mathbf{H}_k^{[i,j]}$ is assumed to be independent and identically distributed (i.i.d.) with $\mathcal{CN}(0,1)$. Additionally, the time-invariant frequency-flat fading is assumed, i.e., channel coefficients are constant during a transmission block and independent to every transmission block. The user j in BS i estimates the channel $\mathbf{H}_k^{[i,j]}$, $k = 1, \cdots, K$, using pilot signals from all BSs. We concentrate on the small scale effects rather than large scale effects to precisely analyze the performance of the proposed CBPS framework in the multi-cell multi-user MIMO networks. As mentioned in Section I-B, because the CBPS framework based on the non-iterative algorithm can be applied to the practical distributed systems, the systematic characteristics of networks can be observed by applying techniques such as handover or radio resource management.

In this study, we assume that there is no estimation error. Each user constructs the transmit beamforming vector using the estimated channel matrices and broadcasted signal subspaces from all BSs, which will discussed in Section III-A1. Moreover, each BS can design a receive beamforming matrix using feedback information from associated users in its cell-range, i.e., the BS only exploits the local CSI to construct the receive beamforming matrix.

The received signal vector at the ith BS can be written as:

$$\mathbf{y}_i = \sum_{j=1}^{S} \sqrt{\beta_i^{[i,j]} P^{[i,j]}} \mathbf{H}_i^{[i,j]} \mathbf{w}^{[i,j]} x^{[i,j]} + \sum_{k=1, k\neq i}^{K} \sum_{m=1}^{S} \sqrt{\beta_i^{[k,m]} P^{[k,m]}} \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} x^{[k,m]} + \mathbf{z}_i, \tag{1}$$

where $P^{[i,j]}$ denotes the transmission power of the user j in BS i and it is limited to the maximum transmit power P. $\mathbf{w}^{[i,j]} \in \mathbb{C}^{L\times 1}$ and $x^{[i,j]}$ denote the unit-norm transmit beamforming vector, and the transmit symbol with unit average power at user j in BS i, respectively. The additive noise which consists of the i.i.d. complex Gaussian with zero mean and the variance of N_0 is denoted by $\mathbf{z}_i \in \mathbb{C}^{M\times 1}$. The average SNR of user j in BS i can be given as $\mathrm{SNR}^{[i,j]} = \left(\beta_i^{[i,j]} P^{[i,j]} \cdot \left\|\mathbf{H}_i^{[i,j]} \mathbf{w}^{[i,j]} x^{[i,j]}\right\|^2\right) \Big/ \left(\|\mathbf{z}_i\|^2\right) = \frac{\beta_i^{[i,j]} P^{[i,j]}}{N_0}$.

III. Proposed CBPS Scheme

In this section, we describe the overall procedure of our proposed CBPS framework followed by the explanation of the transmit beamforming strategy, user scheduling algorithm, and power control technique.

A. Overall Procedure

The proposed framework consists of five steps: Initialization, channel state acquisition, transmit beamforming construction/scheduling metric feedback, user scheduling/ZF receive beamforming design, and power control/uplink data transmissions/decoding. We will provide details on each step next.

1) Initialization: First, we define a signal subspace for BS k as $\mathbf{U}_k = [\mathbf{u}_{k,1}, \cdots, \mathbf{u}_{k,S}] \in \mathbb{C}^{M\times S}$, where $\mathbf{u}_{k,s} \in \mathbb{C}^{M\times 1}$ is the orthonormal basis for $k \in \mathcal{K}$ and $s \in \mathcal{S} = \{1, \cdots, S\}$. The role of $\mathbf{U}_k$ is to manage inter-cell interference by providing the desired signal subspace. In other words, the effect of the inter-cell interference is mitigated by aligning the inter-cell interference with the null-space of the BS's signal subspace, which is called the interference subspace. A simple way to construct the BS's signal subspace is by selecting S columns from the left or right singular vectors of the randomly generated $M \times M$ matrix as $\mathbf{U}_k$ and the remaining $M - S$ columns as the interference subspace. Each BS independently generates a signal subspace regardless of the signal subspace information of other BSs. It should be noted that if each BS constructs a signal subspace in a pseudo-random manner, then there is no need to broadcast signal subspace information to users. The users can know the signal subspace information by the pre-defined signal subspace generating pattern. In addition, since there are enough users in each BS, a user that can improve the sum-rate performance while reducing interference to adjacent BSs can be chosen through the proposed user scheduling algorithm which shall be explained in Section III-C.

2) Channel State Acquisition: In the proposed framework, it is required to estimate the channel state between user j in BS i and BS k, i.e., $\mathbf{H}_k^{[i,j]}$, where $i, k \in \mathcal{K}$ for $i \neq k$. Each user can estimate the channel between the user and all BSs through downlink data transmissions on physical downlink shared channels (PDSCHs) or transmitted CSI-reference signals (CSI-RSs) for downlink channel estimation from BSs, because of the channel reciprocity property in TDD systems. The multiple CSI-RS processes are specified in LTE Release 16 for coordinated multiple-point (CoMP) operations such as coordinated scheduling and beamforming, dynamic point selection, and joint transmission [41]. Based on [41], the *per-CSI-RS-resource feedback*, which individually feeds the CSI back to the network for multiple CSI-RS resources is performed. In our proposed framework, however, the *per-CSI-RS-resource feedback* is not required because the CBPS framework is operated with the local CSI. Consequently, it is enough to estimate the channel state for each user between the user and all BSs based only on the receiving CSI-RSs. The multiple CSI-RS process for multiple BSs with multiple antennas can be implemented by multiplexing resource elements based on the combination of code-domain sharing (CDM), frequency-domain sharing (FDM), and time-domain sharing (TDM) in 5G NR. In addition, the CSI-RS is generated based on a pseudo random sequence [42].

3) Transmit Beamforming Construction and Scheduling Metric Feedback: Based on the estimated channel information and the broadcasted (or pre-determined) signal subspaces, each user can design a transmit beamforming vector. Let $\mathbf{w}^{[i,j]} \in \mathbb{C}^{L\times 1}$ denote a unit-norm transmit beamforming vector of user j in BS i, where $\left\|\mathbf{w}^{[i,j]}\right\|^2 = 1$. The design method of the transmit beamforming vector to achieve the optimal DoF is explained in Section III-B. After the transmit beamforming construction of each user, the value of LIF and an effective channel vector are calculated and fed back to the associated BS as a scheduling metric. The effective channel vector, denoted by $\mathbf{g}_i^{[i,j]} \in \mathbb{C}^{S\times 1}$, is also used for receive beamforming construction at each BS. The CBPS framework only has a few bits needed for feedback: A scalar value of the LIF and an effective channel vector which is S by 1. Additionally, in [43], there is no notable performance gap between using only a few bits for feedback and full feedback. Therefore, the feedback step of the CBPS framework does not incur traffic burden as well as performance degradation.

With the signal subspace $\mathbf{U}_k$ and channel matrix $\mathbf{H}_k^{[i,j]}$, user j in BS i calculates its LIF, which affects BS k as follows:

$$\widetilde{\eta}_k^{[i,j]} = \left\|\mathbf{U}_k^H \mathbf{H}_k^{[i,j]} \mathbf{w}^{[i,j]}\right\|^2, \tag{2}$$

where $i \in \mathcal{K}$, $j \in \mathcal{N}$ and $k \in \mathcal{K}\backslash i$. Note that $\widetilde{\eta}_k^{[i,j]}$ is the amount of interference which user j in BS i causes to BS k. In other words, it is the signals from user j in BS i, which are not aligned with the interference subspace of BS k. The LIF value as the scheduling metric, which indicates the total amount of interference generated from user j in BS i to the inter-cells is written as:

$$\eta^{[i,j]} = \sum_{k=1,k\neq i}^{K} \widetilde{\eta}_k^{[i,j]} = \sum_{k=1,k\neq i}^{K} \left\|\mathbf{U}_k^H \mathbf{H}_k^{[i,j]} \mathbf{w}^{[i,j]}\right\|^2. \tag{3}$$

From the notion of $\mathbf{U}_i$, $\mathbf{H}_i^{[i,j]}$ and $\mathbf{w}^{[i,j]}$, the effective channel vector of user j in cell i, $\mathbf{g}_i^{[i,j]}$, can be calculated as:

$$\mathbf{g}_i^{[i,j]} = \mathbf{U}_i^H \mathbf{H}_i^{[i,j]} \mathbf{w}^{[i,j]}. \tag{4}$$

The effective channel vector represents the received signal after the projection into the signal subspace at the BS.

After the calculation of the scheduling metrics, each user sends uplink control information (UCI), which is composed of CSI, ACK/NACK, and scheduling request, with the scheduling metrics to their associated BSs. UCI can be carried by either the physical uplink control channel (PUCCH) or physical uplink shared channel (PUSCH) based on situations in 5G described in [42]. Generally, the CSI in UCI consists of three major components: Channel quality indicator (CQI), rank indicator, and precoding matrix indicator (PMI) and it is used for determining the modulation coding scheme (MCS) level, precoding matrix, scheduling, and so on. In our proposed framework, however, there is no need to deliver CQI, RI, and PMI through the CSI report, and only the LIF metric and the effective channel vector of each user are transmitted to their associated BS to construct the receive beamforming matrix and perform user scheduling. Since the LIF metric is a scalar and the effective channel vector is a $S \times 1$ vector, there is no big burden to transmit these information.

Furthermore, we can apply any method that reduces feedback overhead in MIMO systems in many types of research [44] and references therein. In [44], the feedback schemes for a single user and multi-user systems with single/multiple antennas were reviewed and the codebook-based feedback schemes for the standard were presented. Moreover, in [16], [33], codebook-based methods were applied for the CBPS framework. By adopting the feedback schemes introduced above, the amount of feedback information can be effectively reduced.

In this study, we assumed perfect feedforward and feedback information exchanges such as various RSs and transmission of UCI/DCI as [29], [32], [33].

4) User Scheduling and ZF Receive Beamforming Design: Based on the received feedback information, i.e., the LIF metrics and effective channel vectors from the N users, each BS selects S users by a scheduling algorithm and constructs the ZF receive beamforming matrix. The specific scheduling algorithm will be presented in Section III-C.

After user scheduling, each BS delivers a set of information, which denotes the time/freqeuncy resource assignment, MCS and transmit power control, for the physical downlink shared channel (PDSCH) and PUSCH through the downlink control information (DCI). From the DCI, selected users determine the modulation order, coding rate, and transmit power for uplink data transmission. In the proposed framework, we can adopt one of the DCI formats in 5G NR [45] without any changes.

In addition, we adopt a linear ZF detection at BSs to perfectly eliminate intra-cell interference when $M \geq S$. Without the loss of generality, the indices of selected users in every cell are assumed to be $(1, \cdots, S)$. Based on the scheduling information and received effective channel vectors $\mathbf{g}_i^{[i,j]}$ which are fed back from the scheduled users, BS i constructs ZF receive beamforming, $\mathbf{F}_i \in \mathbb{C}^{S\times S}$, as follows:

$$\begin{aligned}\mathbf{F}_i &= [\mathbf{f}_{i,1}, \cdots, \mathbf{f}_{i,S}] \\ &\triangleq \left(\left[\underbrace{\mathbf{U}_i^H \mathbf{H}_i^{[i,1]} \mathbf{w}^{[i,1]}}_{\mathbf{g}_i^{[i,1]}}, \cdots, \underbrace{\mathbf{U}_i^H \mathbf{H}_i^{[i,S]} \mathbf{w}^{[i,S]}}_{\mathbf{g}_i^{[i,S]}}\right]^{-1}\right)^H.\end{aligned} \tag{5}$$

5) Power Control, Uplink Data Transmissions, and Decoding: After receiving the DCI from the BSs for scheduling PUSCH, the scheduled users transmit the uplink data to their associated BSs with their transmit power adjusted. The specific power control technique will be explained in Section III-D. At BS i, the received signals are projected to their signal subspaces and then the receive beamforming procedures that aimed to cancel the intra-cell interference are performed. The received signal after the projection to the signal subspace and receive beamforming is represented as

$$\mathbf{r}_i = [r_{i,1}, \cdots, r_{i,S}]^T = \mathbf{F}_i^H \mathbf{U}_i^H \mathbf{y}_i. \tag{6}$$

In (6), the jth spatial stream, $r_{i,j}$, is written as:

$$\begin{aligned} r_{i,j} =& \sqrt{P^{[i,j]}} x^{[i,j]} \\ &+ \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \sqrt{P^{[k,m]}} \mathbf{f}_{i,j}^H \mathbf{U}_i^H \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} x^{[k,m]} \\ &+ \mathbf{f}_{i,j}^H \mathbf{U}_i^H \mathbf{z}_i. \end{aligned} \tag{7}$$

From (7), the achievable rate of the user j in BS i is expressed as

$$R^{[i,j]} = \log\left(1 + \gamma^{[i,j]}\right) = \log\left(1 + \frac{\mathrm{SNR}^{[i,j]}}{\|\mathbf{f}_{i,j}\|^2 + I_{i,j}}\right), \tag{8}$$

where $\gamma^{[i,j]}$ and $I_{i,j}$ denote the signal-to-interference-plus-noise ratio and sum of the residual interference of user j in BS i, respectively. The sum of the residual interference after ZF detection can be written as:

$$I_{i,j} \triangleq \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \left| \mathbf{f}_{i,j}^H \mathbf{U}_i^H \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \right|^2 \cdot \mathrm{SNR}^{[k,m]}. \tag{9}$$

From (8), the total achievable DoF is defined as follows:

$$\mathrm{DoF} = \lim_{\mathrm{SNR}\to\infty} \frac{\sum_{i=1}^{K} \sum_{j=1}^{S} R^{[i,j]}}{\log_2 \frac{P^{\max}}{N_0}}. \tag{10}$$

In this study, we aim to maximize the total achievable DoF, (10), by coordinated beamforming strategy and it shall be explained in Section III-B.

B. Transmit Beamforming Design

To achieve the maximum DoF, we propose a transmit beamforming design strategy and adopt a ZF filtering as a receive beamforming. We then investigate the DoF achievability with the user scaling condition. After estimating the channel matrix at each user, transmit beamforming vectors are determined according to the proposed transmit beamforming strategy. From (8) and (10), the maximum DoF of 1 can be achieved for each user if and only if $I_{i,j}$, for $i \in \mathcal{K}$ and $j \in \mathcal{S}$, remains constant as SNR increases. To obtain the optimal transmit beamforming vector that maximizes the DoF, the lower bound of the achievable rate can be derived using Jensen's inequality as follows:

$$R^{[i,j]} \geq \log_2 \left(\frac{\mathrm{SNR}^{[i,j]} \big/ \|\mathbf{f}_{i,j}\|^2}{1 + \widetilde{I}_i \cdot \frac{P^{\max}}{N_0}} \right), \tag{11}$$

where $\widetilde{I}_i = \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \left\| \mathbf{U}_i^H \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \right\|^2$. Note that $\widetilde{I}_i$ represents the amount of total interference from the inter-cell users before ZF detection at BS i. Now, we can obtain the DoF of 1 for each user if and only if for some $0 \leq \varepsilon < \infty$,

$$\widetilde{I}_i < \varepsilon, \ \forall i \in \mathcal{K}. \tag{12}$$

To satisfy (12), we aim to minimize the sum of interferences at all BSs, i.e., $\min \sum_{i=1}^{K} \widetilde{I}_i$. Based on the definition of $\widetilde{I}_i$ and $\eta^{[i,j]}$, we obtain

$$\begin{aligned} \min \sum_{i=1}^{K} \widetilde{I}_i &= \min \sum_{i=1}^{K} \sum_{k=1,k\neq i}^{K} \sum_{m=1}^{S} \left\| \mathbf{U}_i^H \mathbf{H}_i^{[k,m]} \mathbf{w}^{[k,m]} \right\|^2 \\ &= \min \sum_{i=1}^{K} \sum_{j=1}^{S} \eta^{[i,j]}. \end{aligned} \tag{13}$$

Recollecting (3), the LIF metric of user j in BS i depends only on the transmit beamforming vector $\mathbf{w}^{[i,j]}$ from the signal subspace $\mathbf{U}_i$ and channel matrix $\mathbf{H}_k^{[i,j]}$, for $k \in \mathcal{K}$. Therefore, the right-hand side of (13), can be regarded as the minimization of $\eta^{[i,j]}$, for $i \in \mathcal{K}$ and $j \in \mathcal{S}$. It should be noted that the minimization problem of the sum of interferences at all BSs, $\min \sum_{i=1}^{K} \widetilde{I}_i$, to achieve the maximum DoF for each user can change the minimization problem of the LIF metric for each user, i.e., $\min \eta^{[i,j]}$, for $i \in \mathcal{K}$ and $j \in \mathcal{S}$. Therefore, the transmit beamforming vector of user j in BS i can be chosen as follows:

$$\begin{aligned} \mathbf{w}^{[i,j]} = \arg\min_{\mathbf{w}} \eta^{[i,j]} &= \arg\min_{\mathbf{w}} \sum_{k=1,k\neq i}^{K} \left\| \mathbf{U}_k^H \mathbf{H}_k^{[i,j]} \mathbf{w} \right\|^2 \\ &= \arg\min_{\mathbf{w}} \left\| \mathbf{G}^{[i,j]} \mathbf{w} \right\|^2, \end{aligned} \tag{14}$$

where $\mathbf{G}^{[i,j]} \in \mathbb{C}^{(K-1)S \times L}$ denotes the stacked cross-link channel matrix which consists of the signal subspace and channel matrix, and is written as:

$$\begin{aligned} \mathbf{G}^{[i,j]} = \Bigg[&\left(\mathbf{U}_1^H \mathbf{H}_1^{[i,j]}\right)^T, \cdots, \left(\mathbf{U}_{i-1}^H \mathbf{H}_{i-1}^{[i,j]}\right)^T, \left(\mathbf{U}_{i+1}^H \mathbf{H}_{i+1}^{[i,j]}\right)^T, \\ &\cdots, \left(\mathbf{U}_K^H \mathbf{H}_K^{[i,j]}\right)^T \Bigg]^T. \end{aligned} \tag{15}$$

In (14), the optimal transmit beamforming vector can be obtained through the singular value decomposition (SVD) of $\mathbf{G}^{[i,j]}$. The SVD of $\mathbf{G}^{[i,j]}$ is denoted as

$$\mathbf{G}^{[i,j]} = \mathbf{\Omega}^{[i,j]} \mathbf{\Sigma}^{[i,j]} \mathbf{V}^{[i,j]H}, \tag{16}$$

where $\mathbf{\Omega}^{[i,j]} \in \mathbb{C}^{(K-1)S \times (K-1)S}$ and $\mathbf{V}^{[i,j]} \in \mathbb{C}^{L \times L}$ are unitary matrices and $\mathbf{\Sigma}^{[i,j]} \in \mathbb{C}^{(K-1)S \times L}$ is a diagonal matrix with $\sigma_1^{[i,j]} \geq \cdots \geq \sigma_L^{[i,j]}$ [2]. Accordingly, the optimal transmit beamforming vector $\mathbf{w}^{[i,j]}$ of user j in BS i can designed by the Lth column vector of $\mathbf{V}^{[i,j]}$ as follows:

$$\mathbf{w}^{[i,j]} = \mathbf{v}_L^{[i,j]}. \tag{17}$$

Then, the minimized LIF value for user j in BS i can be obtained by

$$\eta^{[i,j]} = \left(\sigma_L^{[i,j]}\right)^2. \tag{18}$$

[2]Since we assume that $L < (K-1)S + 1$, the diagonal matrix $\Sigma^{[i,j]}$ is a thin matrix. Therefore, $\Sigma^{[i,j]}$ consists of L singular values, $\sigma_1^{[i,j]}, \cdots, \sigma_L^{[i,j]}$.

For some particular antenna configurations at each user, the inter-cell interference can be perfectly eliminated with only transmit beamforming.

Remark: If $L \geq (K-1)S+1$, then the diagonal matrix of $\mathbf{G}^{[i,j]}$, i.e., $\mathbf{\Sigma}^{[i,j]}$, becomes a fat matrix with the rank of $(K-1)S$. Therefore, the singular value corresponding to $\mathbf{v}_L^{[i,j]}$ is zero, and hence the LIF metric $\eta^{[i,j]}$ becomes zero. In other words, if the number of antennas of users is greater than or equal to some constant value related to the number of BSs and scheduled users, then inter-cell interference can be perfectly eliminated by the transmit beamforming strategy. Consequently, we expect the performance of the interference-free networks by the proposed CBPS framework in multi-cell multi-user MIMO networks. In this work, we only consider the case of $L < (K-1)S+1$ since we can predict the performance in the opposite case without ambiguousness.

By the DoF achievability under the user scaling condition [32], the proposed CBPS framework with the transmit beamforming strategy (17) achieves

$$DoF \geq KS, \tag{19}$$

with a high probability if

$$N = \omega\left(SNR^{(K-1)S-L+1}\right), \tag{20}$$

where $f(x) = \omega(g(x))$ implies that $\lim_{x\to\infty} g(x)/f(x) = 0$. The details of proof are described in [32].

C. User Scheduling Algorithm

To select users within a cell range, each BS exploits the effective channel vectors and LIF metrics of users, which are fed back from all users according to Section III-A3. We adopt the concept of the SUS algorithm [38], which can achieve a sum-rate close to the optimal rate of DPC with very low complexity, for the proposed CBPS framework. Therefore, the CBPS framework can enhance the sum-rate performance by the multi-user diversity gain using the user scheduling algorithm. The user scheduling algorithm for the CBPS framework is as follows:

- Step 1 (Initialization): Define the set of users, and initialize s and pseudo orthogonal projection vectors $\widetilde{\mathbf{b}}_1^{[i,j]}$ for all j:

$$\begin{aligned}&\mathcal{N}_1 = \{1,\cdots,N\},\\ &s=1,\\ &\widetilde{\mathbf{b}}_1^{[i,j]} = \mathbf{g}_i^{[i,j]},\ \text{for } j\in\mathcal{N}_1.\end{aligned} \tag{21}$$

- Step 2 (Calculation of orthogonal projection vector): For each user $j \in \mathcal{N}_s$ in cell i, the sth orthogonal projection vector, denoted by $\widetilde{\mathbf{b}}_s^{[i,j]}$, for given $\left\{\mathbf{b}_1^{[i]},\cdots,\mathbf{b}_{s-1}^{[i]}\right\}$ which is a set of previously selected orthogonal projection vectors is calculated as follows:

$$\widetilde{\mathbf{b}}_s^{[i,j]} = \mathbf{g}_i^{[i,j]} - \sum_{s'=1}^{s-1} \frac{\mathbf{b}_{s'}^{[i]H}\mathbf{g}_i^{[i,j]}}{\left\|\mathbf{b}_{s'}^{[i]}\right\|^2}\mathbf{b}_{s'}^{[i]}. \tag{22}$$

- Step 3 (User selection): For the sth user selection, a user with the largest $\left\|\widetilde{\mathbf{b}}_s^{[i,j]}\right\|^2$ is selected from the user pool $\mathcal{N}_s$ with a constraint as follows:

$$\begin{aligned}\pi(s) &= \arg\max_{j\in\mathcal{N}_s}\left\|\widetilde{\mathbf{b}}_s^{[i,j]}\right\|^2,\\ C_1 &: \eta^{[i,j]} \leq \eta_{th}.\end{aligned} \tag{23}$$

  Then, we define $\mathbf{b}_s^{[i]} = \widetilde{\mathbf{b}}_s^{[i,\pi(s)]}$. It should be noted that the first constraint denotes the LIF threshold strategy, i.e., the exclusion of some users from the user pool $\mathcal{N}_s$. Each BS selects a user with the largest effective channel vector, which is mostly orthogonal to the signals of previously selected users. Consequently, a user with a large LIF value can be selected, if the magnitude of the orthogonal component of the effective channel vector of the user is the largest in the user pool. However, the newly selected user may cause interference to neighboring BSs, although the associated BS leads to a high sum-rate performance. Therefore, we exclude users with LIF values greater than the pre-defined LIF threshold in this step. When the LIF threshold strategy is adopted, each BS can set the MCS level based on the pre-defined LIF threshold because users with LIF values greater than the threshold cannot be chosen in the user scheduling. Because the LIF threshold denotes the maximum leakage interference to neighboring BSs from each user, BSs need not consider the entire LIF threshold value.
- Step 4 (Update user pool): If $s < S$, then the $(s+1)$th user pool $\mathcal{N}_{s+1}$ is defined as

$$\begin{aligned}&\mathcal{N}_{s+1} = \{j : j\in\mathcal{N}_s, j\neq\pi(s)\},\\ &s = s+1.\end{aligned} \tag{24}$$

  Repeat Step 2 to Step 4 until $s = S$.

In the user scheduling algorithm, Step 2 and Step 3 can be regarded as the Gram-Schmidth process, since a user with the most orthogonal effective channel vector is selected in Step 2 and Step 3. If the number of users is sufficiently large, the BS can select users whose signals are perfectly orthogonal to each other to improve the performance of the ZF receiver.

Since the proposed CBPS framework consists of cascaded procedures, the user scheduling algorithm can be easily modified by changing the scheduling criterion. For example, to satisfy fairness among users, (23) can be changed as follows:

$$\pi(s) = \arg\max_{j\in\mathcal{N}_s}\frac{R^{[i,j]}(t)}{T^{[i,j]}(t)}, \tag{25}$$

where $R^{[i,j]}(t)$ denotes the instantaneous data rate of user j in BS i at time t and $T^{[i,j]}(t)$ denotes the long-term average data rate of user j in BS i at time t. The long-term average achievable data rate is recursively computed by

$$\begin{aligned}T^{[i,j]}(t) = &\left(1-\frac{1}{t_c}\right)T^{[i,j]}(t-1)\\ &+\frac{1}{t_c}R^{[i,j]}(t-1)\cdot\mathcal{I}(j=\pi(s)),\end{aligned} \tag{26}$$

where t_c denotes the time window over which fairness is imposed and $\mathcal{I}(\cdot)$ denotes the indicator function.

D. Power Control Technique

In the previous section, users with LIF values greater than the LIF threshold are excluded from the user pool regardless of the desired signal strength. When the LIF value of a user is greater than the LIF threshold, the user can remain in the user pool in scheduling procedure by lowering its transmit power. Consequently, the transmit power of user j in BS i is determined as follows:

$$P^{[i,j]} = \begin{cases} \frac{\eta_{th}}{\eta^{[i,j]}} \cdot P, & \eta^{[i,j]} > \eta_{th} \\ P, & \text{otherwise} \end{cases}. \quad (27)$$

Therefore, the LIF values of all users cannot exceed the LIF threshold. With the proposed power control technique, instead of excluding the users, the transmit power of users whose LIF is greater than the threshold is reduced, making the number of schedulable users greater than the schedulable number of users in CBS which denotes the CBPS without power control. In other words, the cardinality of user pool, $|\mathcal{N}_s|$ always set to be N. Better energy efficiency as well as sum-rate performance can be achieved by the proposed power control.

IV. COMPARISION OF COMPUTATIONAL COMPLEXITY AND SIGNALING OVERHEAD

In this section, we discuss the computational complexity and amount of signaling overhead of the two proposed frameworks with existing schemes [46]. The computational complexity should be analyzed for both the user and BS separately. The signaling overhead is also investigated by being classified as feedforward (i.e., from BS to user) and feedback (i.e., from user to BS). In the user side, transmit beamforming vectors are constructed and scheduling metrics that consists of LIF metrics and effective channel vectors are calculated.

A. Computational Complexity Analysis

In each BS, users are selected through the user scheduling algorithm and receive beamforming vectors are designed. After data transmission, the BSs project the received signal to their signal subspace and then the receive beamforming procedures are performed. We assume that the addition, subtraction, multiplication, and division of real numbers costs one floating point operation (flop) and the multiplication of complex numbers costs six flops.

1) CBPS Scheme: Each user calculates the transmit beamforming vector (14) based on (15). From [47], we can easily notice that the calculation of (15) requires $8(K-1)MLS - 2(K-1)LS$ flops, which results in $O(KMLS)$. As mentioned in Section III-B, the transmit beamforming vectors can be obtained by SVD operation with $O(KL^2S)$ based on the Householder reflections and QR decomposition method [48]. Consequently, the overall computational complexity for each user is $O(KMLS + KL^2S)$.

Based on the received scheduling metrics, each BS selects S. The iteration of the user scheduling requires $(S^3 + 50S^2 - 6S)$ flops denoted as $O(S^3)$. After the BSs send the scheduling information to their associated users, each BS constructs the ZF receive beamforming (5). The calculation of $\left(\mathbf{F}_i^H\right)^{-1}$ requires $(8MLS + 8MS^2 - 2MS - 2S^2)$ flops and the inverse of the $S \times S$ matrix requires $O(S^3)$. For the ZF receive beamforming, the $O(MLS + MS^2 + S^3)$ calculation is needed. From (6), the calculation of $r_{i,j}$ requires $(8MS + 8S^2 - 4S)$ flops, which implies $O(MS + S^2)$. Therefore, the overall computational complexity at each BS is $O(MLS + MS^2 + S^3)$.

2) C-ICPA-OIA and R-ICPA-OIA [46]: The C-ICPA-OIA and R-ICPA-OIA denote the coarse intra-cluster performance aware OIA and the refined intra-cluster performance aware OIA, respectively and the details of both schemes are described in [46]. We consider the overall computational complexity of C-ICPA-OIA and R-ICPA-OIA except in energy harvesting procedures. In C-ICPA-OIA, each user calculates a metric for the transmit beamforming vector with $(16KMLS + 8KL^2S - 4KLS - 2KL^2)$ flops, so $O(KMLS + KL^2S)$. After the generalized eigenvalue decomposition operation, the complexity of the transmit beamforming construction is $O(KMLS + KL^2S + L^3)$. For R-ICPA-OIA, each user calculates S metrics for user scheduling and then feedback to its BS. Therefore, the overall complexity for each user is $O(KMLS + KL^2S + L^3S)$.

In each BS, since the procedures of the ZF receive beamforming and projection to signal subspace are similar for the proposed work and there is no significant burden to perform the user scheduling algorithm, there is no difference in the overall computational complexity.

B. Signaling Overhead

For the proposed CBPS framework, there are several information exchange procedures for uplink data transmissions. We assume that two scalar values are required for the representation of one complex number.

1) CBPS Scheme: In the initialization step III-A1, BS i generates the own signal subspace $\mathbf{U}_i$ and feeds it forward to all users. If the information of the signal subspace is known, then the interference subspace is automatically known and vice versa. Accordingly, each user can distinguish the signal subspace with $\min\{M-S, S\}$ normal vectors with $M \times 1$. As mentioned in Section III-A1, if the signal subspace is constructed in a pseudo random manner, there is no feedforward signaling.

Each user feeds the LIF metric and effective channel vector information back to its associated BS for user scheduling. Based on (3) and (4), the LIF metric and effective channel vector are quantified as a scalar value and S complex numbers, respectively. Therefore, the overall signaling overhead from each user to the BS is $(1 + 2S)$.

2) C-ICPA-OIA and R-ICPA-OIA [46]: The C-ICPA-OIA scheme also requires $\min\{M-S, S\}$ normal vectors with $M \times 1$ for broadcasting the signal subspace per BS, whereas the MS complex numbers are needed for R-ICPA-OIA because the column vectors of the signals subspace are directly used for the construction of transmit beamforming vectors and the user scheduling procedures in R-ICPA-OIA.

In addition, there is a 1 scalar value fed back from a user in C-ICPA-OIA for the user scheduling and the $S \times 1$ effective channel vector should be fed back for information decoding at

TABLE I
COMPUTATIONAL COMPLEXITY AND THE AMOUNT OF INFOMATION EXCHANGE OF THE DIFFERENT SCHEMES

			C-ICPA-OIA [46]	R-ICPA-OIA [46]	CBPS
Computational complexity	At each user		$O(KMLS + KL^2S + L^3)$	$O(KMLS + KL^2S + L^3S)$	$O(KMLS + KL^2S)$
	At each BS		$O(MLS + MS^2 + S^3)$	$O(MLS + MS^2 + S^3)$	$O(MLS + MS^2 + S^3)$
Signaling overhead in terms of scalar value	Feedforward (BS→user)	Pure random	$2\min\{M-S, S\}M$	$2MS$	$2\min\{M-S, S\}M$
		Pseudo random	0	0	0
	Feedback (user→BS)		$1+2S$	$3S$	$1+2S$

BSs where the ZF receive beamforming strategy is exploited. In case of R-ICPA-OIA, S scheduling metrics are sent to the associated BS for user scheduling and also, the $S\times 1$ effective channel vector is transmitted from a user to the associated BS. Consequently, the signaling overhead for feedback in C-ICPA-OIA and R-ICPA-OIA is $(1+2S)$ and $(3S)$, respectively.

In summary, the computational complexity and signaling overhead, which consists of the feedforward and feedback of the proposed CBPS framework are much lower than those of the other existing schemes, as specified in Table I.

V. SIMULATION RESULTS

A. Simulation Environment

In this section, we present the performance of the proposed framework compared with existing schemes, which include SVD-based OIA [32], C-ICPA-OIA, and R-ICPA-OIA [46]. It is assumed that $\beta_k^{[i,j]} = 1$ for $k = i$ and $\beta_k^{[i,j]} = 0.5$ for $k \neq i$ as [46]. In the SVD-based OIA scheme, the transmit beamforming vectors are constructed by performing the SVD of the effective channel matrix and S users are selected with the S smallest LIF metrics by a BS. In the C-ICPA-OIA and R-ICPA-OIA schemes, harvested energy as well as the sum-rate are considered for simultaneous wireless information and power transfer (SWIPT). For fair comparison, energy harvesting is neglected in the C-ICPA-OIA and R-ICPA-OIA schemes. Consequently, a metric, $M_{i,j}^C$, for the construction of transmit beamforming vectors and user scheduling for C-ICPA-OIA becomes signal-to-generating-interference ratio (SGIR) and it can be written as

$$M_{i,j}^C = \frac{\left\| \mathbf{U}_i^H \mathbf{H}_i^{[i,j]} \mathbf{w} \right\|^2}{\sum\limits_{k=1,k\neq i}^{K} \left\| \mathbf{U}_k^H \mathbf{H}_k^{[i,j]} \mathbf{w} \right\|^2} = \frac{\mathbf{w}^H \mathbf{A}^{[i,j]} \mathbf{w}}{\mathbf{w}^H \mathbf{B}^{[i,j]} \mathbf{w}}, \tag{28}$$

where

$$\mathbf{A}^{[i,j]} = \mathbf{H}_i^{[i,j]H} \mathbf{U}_i \mathbf{U}_i^H \mathbf{H}_i^{[i,j]},$$
$$\mathbf{B}^{[i,j]} = \sum_{k=1,k\neq i}^{K} \mathbf{H}_k^{[i,j]H} \mathbf{U}_k \mathbf{U}_k^H \mathbf{H}_k^{[i,j]}.$$

The transmit beamforming vector of each user is determined as a vector maximizing SGIR, and S users with S largest SGIRs are selected in the C-ICPA-OIA scheme. In (28), $\text{SGIR}^{[i,j]}$ can be regarded as a Rayleigh quotient of above two symmetric matrices $\mathbf{A}^{[i,j]}$ and $\mathbf{B}^{[i,j]}$, and an optimal $\mathbf{w}$ can be obtained by generalized eigenvalue decomposition. In the R-ICPA-OIA scheme, a metric for the construction of transmit beamforming vectors and the user scheduling of user j in BS i can be described as follows:

$$M_{i,j}^R(s) = \frac{\left| \mathbf{u}_i^{[s]H} \mathbf{H}_i^{[i,j]} \mathbf{w} \right|^2}{\sum\limits_{k=1,k\neq i}^{K} \left\| \mathbf{U}_k^H \mathbf{H}_k^{[i,j]} \mathbf{w} \right\|^2}, \tag{29}$$

where $\mathbf{u}_i^{[s]}$ denotes the sth basis vector ($1 \le s \le S$) of signal subspace $\mathbf{U}_i$. In (29), each user should know the exact basis vector of the signal subspace to determine its transmit beamforming vector and signaling overhead is inevitable to provide exact basis vectors as mentioned in Section IV. In addition, because each user has to perform S calculations, a complexity issue may occur. The compared schemes (i.e., SVD-based OIA, C-ICPA-OIA and R-ICPA-OIA) exploit ZF-based receive beamforming for decoding uplink data. For more details on each conventional scheme, refer to [32], [46].

Regarding practical systems, we consider the imperfect CSI at BSs as

$$\widehat{\mathbf{H}}_k^{[i,j]} = \mathbf{H}_k^{[i,j]} + \mathbf{\Delta}_k^{[i,k]}, \tag{30}$$

where $\mathbf{\Delta}_k^{[i,k]}$ denotes the error component. Each element of the estimation error $\mathbf{\Delta}_k^{[i,j]}$ is assumed to be Gaussian with zero-mean and covariance matrix, i.e., $\mathcal{CN}(0,\delta)$ where δ denotes the variance of the channel estimation error. We evaluated the performance of CBPS with conventional schemes with the case of $\delta = 0.1$ as [34]. In Fig. 2 – Fig. 5, the dot lines represent the case of perfect CSI, whereas the solid lines represent the case of imperfect CSI.

Remark: The pilot contamination, which causes the channel estimation error, results from the reuse of the non-orthogonal pilot sequence across cells because of the limited channel coherence time. As a result, pilot contamination occurs in massive MIMO networks or massive user environments, and many types of research have been conducted to address the problem of pilot contamination [14], [49]–[53]. In the CBPS framework, the effect of pilot contamination can be regarded as insignificant, since the small number of users are scheduled at the same time and the small number of antennas is considered. Nevertheless, the system performance can be guaranteed using appropriate pilot sequence design.

B. Simulation Results

Fig. 2 shows the number of users in a cell versus the sum of LIF values, i.e., $\sum_{i=1}^{K}\sum_{j=1}^{S}\eta^{[i,j]}$, when $K=4$, $M=4$, $L=2$, $S=2$, $P/N_0 = 20$ dB. We compare CBPS without the power control technique, which is referred to as CBS, and

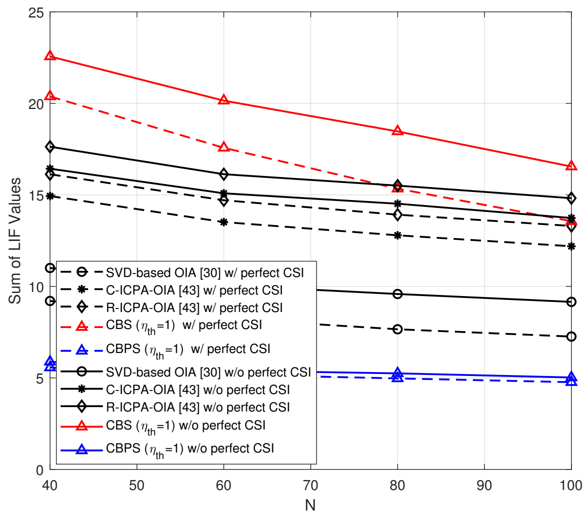
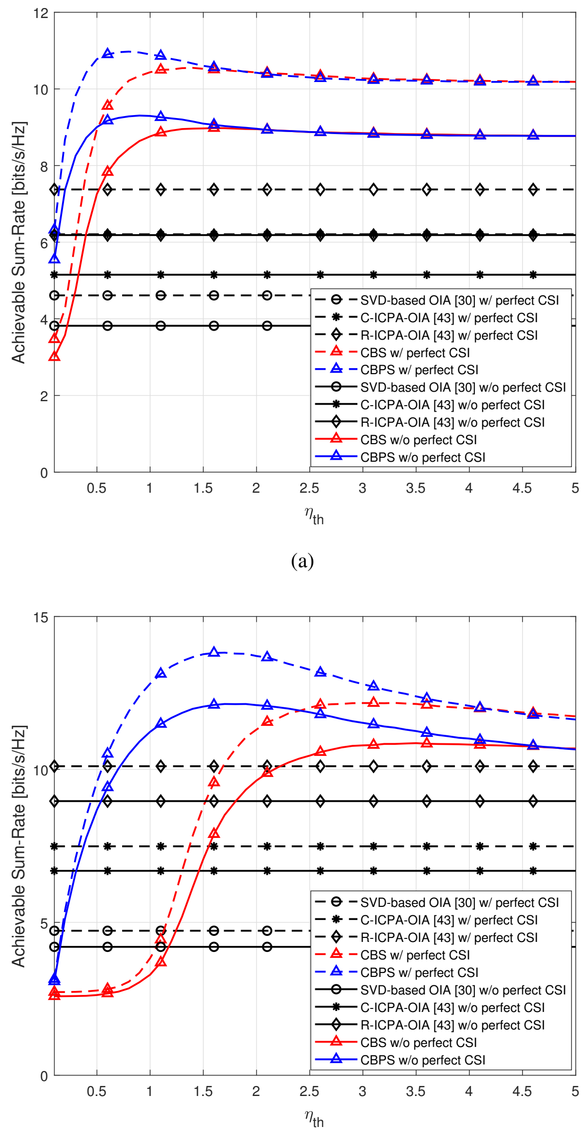


Fig. 2. Number of users versus sum of LIF values when $K = 4, M = 4, L = 2, S = 2, P/N_0 = 20$ dB.



(a)

(b)

Fig. 3. LIF threshold value versus achievable sum-rate when $M = 4, L = 2, S = 3, P/N_0 = 0$ dB, for (a) $K = 2, N = 40$ and (b) $K = 3, N = 100$.

the CBPS framework with existing schemes: SVD-based OIA, C-ICPA-OIA and R-ICPA-OIA. The sum of LIFs of all the schemes with perfect CSI are lower than those of all schemes without perfect CSI. In addition, the sum of the LIFs of all schemes decrease as the number of users increases owing to multi-user diversity gain. By applying a power control technique, the sum of LIFs can be remarkably reduced as shown in Fig. 2.

Fig. 3 depicts the achievable sum-rate with respect to the LIF threshold value, η_{th}, when $M = 4$, $L = 2$, $S = 3$, $P/N_0 = 0$ dB, for (a) $K = 2, N = 40$ and (b) $K = 3$, $N = 100$. SVD-OIA, C-ICPA-OIA, and R-ICPA-OIA schemes remain constant with the increasing LIF threshold, because the threshold is not considered in those schemes. In Fig. 3, when value of η_{th} is small, the transmission power of most users is scaled, and there is no user with LIF greater than the small value of η_{th}. For this reason, the performance gap between the case of perfect CSI (dot lines) and the case of imperfect CSI (solid lines) is small. As the value of η_{th} increases, the performance gap between the case of perfect CSI and the case of imperfect CSI also increases and then converges. In addition, because the number of users that can be scheduled in Fig. 3(b) is greater than in Fig. 3(a), the degree of freedom for user scheduling is greater. Therefore, in the case of Fig. 3 (b), it can be seen that the performance gaps between the perfect CSI and the imperfect CSI is smaller for both CBS and CBPS than in the case of Fig. 3 (a). Also, there exist optimal LIF threshold values for the CBS and CBPS frameworks. The optimal LIF threshold values in Fig. 3(a) are lower than those in Fig. 3(b), because the inter-cell interference is stronger when the number of BSs is large. Also, the optimal LIF threshold value of CBS is larger than that of the CBPS framework. This is because all users can be candidates for user scheduling by a power control technique in the CBPS regardless of the LIF threshold value. In contrast, the selection of a small LIF threshold keeps a large number of users from being excluded by user scheduling when power control is not applied, resulting in sum-rate performance degradation.

In Fig. 4, the achievable sum-rate performance is shown for various numbers of users in a BS where the optimal LIF threshold values, η^*_{th}, are adopted for CBS and CBPS, when $K = 3, M = 4, L = 2, S = 3$, and $P/N_0 = 20$ dB. As the number of users per cell increases, the achievable sum-rate increases owing to the effect of multi-user diversity. Also, the case of a perfect CSI shows better sum-rate performance for all schemes. The proposed methods exhibit a higher sum-rate than existing schemes, and CBPS with the optimal LIF threshold shows the best sum-rate performance for any N. It should be noted that the average sum-rate of CBPS with optimal LIF threshold is approximately 19.5% higher than that of CBPS where the LIF threshold value is set to 2. Therefore, it can be observed that the LIF threshold is one of the major factors for

TABLE II
OPTIMAL LIF THRESHOLD ACCORDING TO P/N_0

P/N_0		0 dB	5 dB	10 dB	15 dB	20 dB	25 dB	30 dB
CBS	$K=2$	1.4	0.9	0.7	0.6	0.6	0.6	0.6
	$K=3$	3.5	3.4	3.3	3.0	3.0	3.0	3.0
CBPS	$K=2$	0.8	0.5	0.3	0.2	0.1	0.1	0.1
	$K=3$	1.9	1.4	1.0	0.8	0.6	0.5	0.4

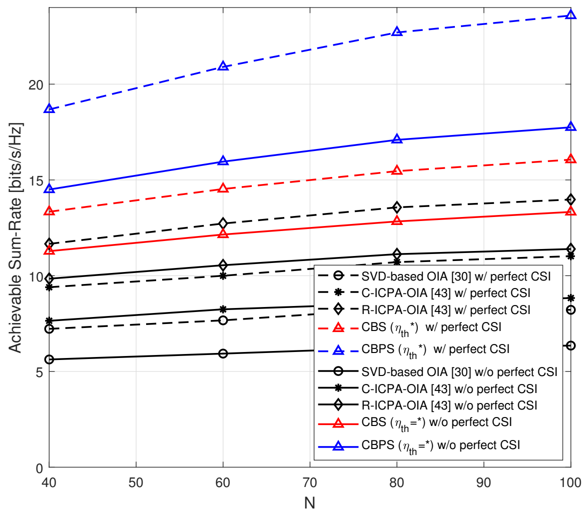


Fig. 4. Number of users versus achievable sum-rate when $K=3, M=4, L=2, S=3, P/N_0=20$ dB.

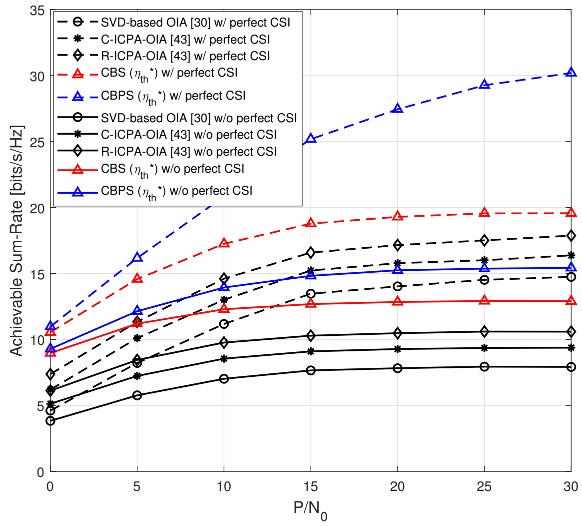
network performance.

Fig. 5 shows the achievable sum-rate according to the change in maximum SNR value, P/N_0, when $M=4, L=2, S=3, N=40$ for (a) $K=2$ and (b) $K=3$. As shown above, the achievable sum-rate performance when perfect CSI is assumed is superior to the case with channel estimation error. Since inter-cell interference cannot reach zero when the number of users in a cell is fixed, the sum-rates are saturated in the sufficiently high SNR regime. As shown Table II, the optimal LIF threshold values for $K=2$ are lower than those for $K=3$, because of the high inter-cell interference when $K=3$. In addition, it can be observed that as the SNR increases, the inter-cell interference increases, and thus optimal LIF threshold values are reduced so that the interference cannot affect the neighboring BSs.

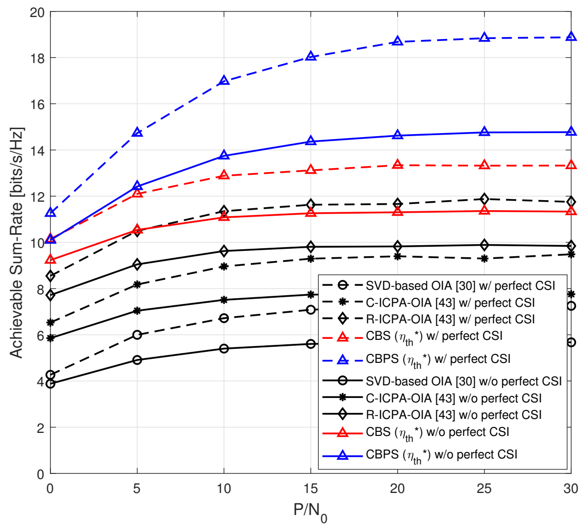
Consequently, the following observations can be made from Fig. 5. When $K=2$, the sum-rate of CBPS with $\eta_{th}=0.4$ (dash-dotted line) approaches to that of CBPS with optimal LIF threshold (solid line) in the low SNR regime, as shown in Fig. 5(a). When $K=3$, CBPS with $\eta_{th}=0.4$ shows a sum-rate similar to CBPS with the optimal LIF threshold in the high SNR regime, as shown in Fig. 5(b).

C. Discussion

In the two schemes proposed in [46], a user with a large SGIR value is selected and the transmit beamforming vector of the selected user is constructed to maximize the SGIR value. The C-ICPA-OIA scheme, does not take the effect of ZF decoding into account and only deals with the overall signal strength within the signal subspace as a coarse description of the user's effective signal strength. It is not the desired signal strength in the signal subspace, but the effective signal strength projected on a specific basis of the signal subspace after ZF decoding. To compensate for this disadvantage, R-ICPA-OIA tries to guarantee orthogonality between the users' uplink signals using the basis information of the signal subspace.



(a)



(b)

Fig. 5. SNR versus achievable sum-rate when $M=4, L=2, S=3, N=40$, for (a) $K=2$ and (b) $K=3$.

In R-ICPA-OIA, however, by defining the basis of the signal subspace in advance, the advantage of the degree of freedom when setting the basis set is reduced. In the proposed CBPS, the transmit beamforming vector is constructed to minimize LIF, and users are selected by maximizing the orthogonality between the signal vector of users without defining the basis of the signal subspace in advance. Therefore, CBPS can show better performance in terms of the sum-rate than conventional schemes such as C-ICPA-OIA and R-ICPA-OIA.

VI. Conclusion

In this study, we proposed an interference-aware CBPS framework for multi-cell MIMO uplink cellular networks. In the proposed framework, inter-cell interference was efficiently mitigated by transmit beamforming based on the SVD operation of stacked cross-link channel information and intra-cell interference was eliminated by the ZF receive beamforming whereas the spectral efficiency is improved by the user scheduling algorithm where the effective channel vectors of users are orthogonally projected with the efficient power control technique. Furthermore, through complexity analysis, the CBPS framework showed its superiority over other schemes. Extensive simulations reveal that the proposed framework considerably outperforms a small amount of signaling overhead compared with the existing schemes and can be applied with better performance for practical 5G NR systems. The proposed CBPS framework can be combined with the MMSE receiver instead of the ZF receiver and the proposed CBPS framework can be combined with non-orthogonal multiple access (NOMA) for the case of $M < S$. For future work, we will consider the pilot contamination effect for massive MIMO networks and analyze the systematic characteristics of networks such as user distribution, mobility, etc.

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